

# APPARATUS AND METHOD FOR FRICTION STIR WELDING WITH A VARIABLE SPEED PIN

## BACKGROUND OF THE INVENTION

### 1) Field of the Invention

The present invention relates to friction welding and, more specifically, to an apparatus and method for friction stir welding with a pin having a variable rotational speed.

### 2) Description of Related Art

Friction stir welding is a process in which a rotating tool, such as a pin or probe, is urged into and/or through a workpiece, e.g., to join multiple members of the workpiece in a solid state or to repair cracks in a workpiece. Typically, the pin extends from a shoulder, which can be flat, concave, or otherwise contoured, and the shoulder is urged against the workpiece so that the pin is urged therein. The pin is then urged through the workpiece to form a continuous weld joint. For example, during one conventional friction stir welding process, the probe of the rotating tool is plunged into a workpiece or between two workpieces by a friction stir welding machine to produce the required resistance force to generate sufficient frictional heating to form a region of plasticized material. The tool can be tilted approximately 3° relative to the workpiece such that the trailing edge of the shoulder is thrust into and consolidates the plasticized material. Upon solidification of the plasticized material, the members of the workpiece are joined along the weld joint. The magnitude of force exerted by the friction stir welding tool must be maintained above a prescribed minimum in order to generate the required frictional heating. Friction stir welding is further described in U.S. Patent No. 5,460,317 to Thomas et al., the contents of which are incorporated herein by reference.

Some friction stir welding pins define helical threads, which can be right-hand threads, left-hand threads, or a combination thereof. Generally, the threads increase

the mixing of the plasticized material in the region of the weld joint. Further, a support device is often provided behind the weld joint, e.g., an anvil or other backing device provided opposite the shoulder, to prevent deformation of the workpiece by the forces exerted by the friction stir welding tool and maintain dimensional tolerances.

- 5 The shoulder and the backing device are typically urged together during welding to prevent material that is plasticized by the friction heat generated by the welding tool from flowing out of the weld joint. The inward clamping of the shoulder and backing device also consolidates the joint to minimize porosity and provide a weld joint having the desired surface finish.

10 A welding machine that is used to move the friction stir welding tool through the workpiece must often exert significant forces on the welding tool to move the welding tool at a particular speed through the workpiece. The force can depend in part on the thickness of the workpiece, the material of the workpiece, the length and diameter of the pin of the tool, the rotational speed of the tool, the speed of the tool  
15 through the workpiece, and the like. The forces required to achieve a particular weld joint can limit the speed at which the machine can be operated and, hence, the speed at which the joint can be formed. Further, the machine and tool typically require periodic maintenance and/or replacement, especially where the forces on the machine and the tool are significant.

20 Thus, conventional friction stir welding devices have been shown to form weld joints in which the material of the workpiece is plasticized and mixed, and the resulting granular structure in the weld joint is refined. However, a need continues to exist for an improved friction stir welding tool for forming weld joints in which the material has been optimally mixed and refined. The tool should allow for friction stir welding of a variety of workpieces, including thick workpieces, using a variety of welding machines and tools. The tool should be capable of effectively plasticizing and mixing the material. Preferably, the tool should also be compatible with features  
25 and methods for reducing the forces on the tool and machine during welding.

30 **SUMMARY OF THE INVENTION**

The present invention provides an apparatus and method for forming a friction stir weld joint in a workpiece. The apparatus includes a friction stir welding pin that is rotated and urged against the workpiece. Further, the rotational speed of the

friction stir welding pin is adjusted cyclically and/or according to a predetermined schedule.

According to one embodiment of the present invention, the method includes adjusting the rotational speed of the pin between first and second predetermined speeds cyclically and/or in accordance with a predetermined schedule, the first speed being less than 99% of the average speed of the pin and the second speed being greater than 101% of the average speed of the pin. Further, the rotational direction of the pin can be reversed cyclically during operation. The rotational speed of the pin can be adjusted at a frequency of between about 0.1 Hz and 100 Hz, and the cyclic adjusting can be sinusoidal. For example, the rotational speed of the pin can be adjusted by varying an electric current supplied to an actuator that rotates the pin. Further, the workpiece can be heated before friction stir welding, e.g., by an induction heater.

The workpiece can be formed of various materials such as aluminum, 15 aluminum alloys, titanium, titanium alloys, steel, or iron-nickel alloys.

The present invention also provides a friction stir welding apparatus that includes a rotatable pin structured to be urged against a workpiece to friction stir weld the workpiece, an actuator configured to rotate the pin, and a controller configured to adjust the actuator and thereby adjust a rotational speed of the pin according to a predetermined schedule. The controller can be configured to cyclically adjust the actuator and thereby adjust the rotational speed between first and second predetermined speeds, e.g., by adjusting an electric current provided to the actuator. The apparatus can also include a heater, such as an induction heater, configured to heat the workpiece.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages and features of the invention, and the manner in which the same are accomplished, will become more readily apparent upon consideration of the following detailed description of the invention taken in conjunction with the accompanying drawings, which illustrate preferred and exemplary embodiments, but which are not necessarily drawn to scale, wherein:

Figure 1 is a perspective view illustrating a friction stir welding tool according to one embodiment of the present invention configured for friction stir welding two workpieces;

Figure 2 is a graph illustrating the variation in the rotational speed of the pin during friction stir welding according to one embodiment of the present invention;

5       Figure 3 is a graph illustrating the variation in the rotational speed of the pin during friction stir welding according to another embodiment of the present invention, in which the pin cyclically reverses direction;

Figure 4 is an elevation view illustrating a friction stir welding tool according to another embodiment of the present invention, the tool having a pin with two independently rotatable portions;

10      Figure 5 is an elevation view illustrating a friction stir welding tool according to yet another embodiment of the present invention, the tool having a pin with two portions of dissimilar diameters; and

Figure 6 is an elevation view illustrating a friction stir welding tool according to still another embodiment of the present invention, the tool having a pin with three portions.

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#### DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring now to the drawings and, in particular, to Figure 1, there is shown 25 an apparatus **10** for friction stir welding a workpiece **60** according to one embodiment of the present invention. The friction stir welding apparatus **10** includes a friction stir welding tool **20**, and at least one actuator **30** for rotating the tool **20** and moving the tool **20** through the workpiece **60** to form a friction weld joint **80**. For example, the friction stir welding tool **20** can be engaged to a chuck, spindle, or other member **32** 30 that is engaged to the actuator **30**. The actuator **30** can be any of various types of actuating devices, including electric, hydraulic, or pneumatic devices, any of which can include a mechanical linkage. For example, the actuator **30** can be part of a machine, such as a milling machine or a drill, that is structured for rotating and moving the friction stir welding tool **20**. The actuator **30** be operated manually, but

preferably is operated by a computer, microprocessor, microcontroller or other controller **50**, which can be programmed to operate according to a schedule such as a schedule stored in or created by a computer software program.

The term “workpiece” is not meant to be limiting, and it is understood that the workpiece **60** can include one or more structural members **62, 64**, which can be configured in various configurations. For example, as shown in Figure 1, the edges **66, 68** of the two structural members **62, 64** can be positioned in abutting contact to form an interface **70** therebetween that can be welded to form the joint **80**, e.g., a butt weld joint as shown in Figure 1. Alternatively, other types of joints **80** can similarly be formed using the apparatus **10** of the present invention. For example, a lap joint can be formed by overlapping faying surfaces of the structural members **62, 64** and welding through an interface of the faying surfaces to form a lap joint that extends along the interface. The structural members **62, 64** can also be positioned and welded in other configurations, and any number of structural members **62, 64** can be joined by the joint **80**. In another embodiment, the workpiece **60** can include a single structural member and the friction stir welding apparatus **10** can be used to form a weld joint in the member, e.g., to repair a crack, hole, or other defect therein or to affect the material properties of the structural member.

The structural members **62, 64** can be formed of a variety of materials including, but not limited to, aluminum, aluminum alloys, titanium, titanium alloys, steel, and the like. Non-metal materials can also be welded with the friction stir welding apparatus **10**, e.g., materials such as polymers and the like. Further, the workpiece **60** can include members of similar or dissimilar materials, for example, structural members **62, 64** formed of different metals, including metals that are unweldable or uneconomical to join by conventional fusion welding techniques. Unweldable materials, when joined by conventional fusion welding techniques, produce relatively weak weld joints that tend to crack during weld solidification. Such materials include aluminum and some aluminum alloys, particularly AA series 2000 and 7000 alloys. The use of friction stir welding permits workpieces formed of unweldable materials to be securely joined. Friction stir welding also can be used to securely join weldable materials to other weldable and to unweldable materials. Thus, the materials that form the workpiece **60** can be chosen from a wider variety of light weight, high strength metals and alloys, thereby facilitating reduction of the overall weight of the workpiece **60** and a structural assembly formed therefrom.

The workpieces **60** formed according to the present invention can be used in a variety of applications, including, for example, frames, panels, skins, airfoils, and the like for aeronautical and aerospace structures such as aircraft and spacecraft, for marine vehicles, automobiles, and the like, as well as for other applications outside of the transportation industry. The friction stir welding apparatus **10** of the present invention can be used for friction stir welding large workpieces and workpieces having curvilinear geometries. In some applications, the members **62**, **64** are joined in geometrical configurations that make difficult, or prevent, access to the opposing sides of the workpiece **60**. For example, the structural members **62**, **64** can be joined to form a partially or fully closed body such as a tube or an airplane wing.

As illustrated in Figure 1, the friction stir welding tool **20** includes a shoulder **22** and a pin **24** extending therebetween. The pin **24** and shoulder **22** are preferably formed of a material having high strength and heat resistance. For purposes of example only and not limitation, the pin **24** and/or shoulder **22** can be constructed of tool steel, a molybdenum alloy, such as TZM, nickel alloys, such as Rene 41 (UNS N07041), and iron-nickel alloys. The shoulder **22** is structured to be urged against the workpiece **60** such that the pin **24** is inserted into the workpiece **60**, e.g., into the interface **70** as shown in Figure 1. In other embodiments of the invention, the tool **20** can include first and second shoulders that are structured in an opposed configuration with a pin extending between the shoulders such that the shoulders can be disposed opposite the workpiece **60** and frictionally engaged to opposite surfaces of the workpiece **60** therebetween. In either case, each shoulder **22** of the apparatus **10** can define a surface that is generally flat, tapered, concave, convex, or otherwise shaped, e.g., to engage the workpiece **60** and prevent “plowing,” in which plasticized material from the workpiece **60** is pushed radially outside the circumference of the shoulder **22** as the tool **20** is moved along the workpiece **60**. Further, each shoulder **22** can define one or more frictional features, e.g., raised portions or surfaces such as threads, bumps, or ribs that are structured to frictionally engage the workpiece **60**. For example, a spiral thread can be provided on each shoulder **22** to engage the workpiece **60**. The pin **24** also defines a stirring portion that engages the workpiece **60** during welding. The stirring portion of the pin **22** can be cylindrical or can define a variety of shapes and contours including helical threads, circumferential grooves, ridges, tapers, steps, and the like.

The actuator 30 is configured to rotate the tool 20 and, hence, the pin 24 at a variable rotational speed, which can be controlled by the controller 50. For example, in one embodiment of the present invention, the actuator 30 can be configured to rotate the pin 24 at an average speed  $S_{avg}$  of between about 0 and 3000 revolutions per minute (RPM) in either rotational direction, though in some embodiments, the pin 24 may rotate at speeds that are faster than the foregoing range of speeds. Further, the rotational speed of the pin 24 can be varied throughout a welding operation. For example, as illustrated in Figure 2, the rotational speed of the pin 24 is increased during an initiation period 100 between times  $T_0$  and  $T_1$  at the start of a welding 10 operation. Thereafter, the rotational speed of the pin 24 is cyclically adjusted or modulated, between a minimum speed  $S_{min}$  and a maximum speed  $S_{max}$ . For example, the rotational speed of the pin 24 can be decreased to the minimum speed  $S_{min}$  at times  $T_2$ ,  $T_4$ ,  $T_6$ , and increased to the maximum speed  $S_{max}$  at times  $T_3$ ,  $T_5$ ,  $T_7$ .

The cyclical variation can be sinusoidal, as illustrated in Figure 2, such that 15 the rotational speed of the pin 24 varies between the minimum speed  $S_{min}$  and the maximum speed  $S_{max}$  and has an average rotational speed  $S_{avg}$  midway therebetween. The frequency of the variation is defined by the number of cycles of variation per second, expressed in hertz (Hz). During one cycle of variation, the rotational speed of the pin 24 increases from the minimum speed  $S_{min}$  to the maximum speed  $S_{max}$  and 20 thereafter slows from the maximum speed  $S_{max}$  to the minimum speed  $S_{min}$ . The frequency of variation in rotational speed of the pin 24 can be adjusted according to the thickness, material, or other mechanical properties of the workpiece 60, the speed at which the pin 24 is moved through the interface 70 to form the weld, the size and surface contour of the pin 24, the temperature of the workpiece 60, the rotational 25 speed and variation in speed of the pin 24, the size and type of weld joint 80 being formed, the desired mechanical properties of the weld joint 80, and the like. For example, the frequency of variation can be increased for welding workpieces 60 having structural members 60, 62 with dissimilar material properties such as dissimilar grain sizes. In addition, the frequency of variation can be determined in 30 part according to the angular separation of features on the pin 24, such as planar surfaces extending axially along the pin 24, or according to the pitch of threads defined by the pin 24. According to one embodiment of the present invention, the frequency of variation can be between about 0.1 Hz and 100 Hz.

The amplitude of the variation in rotational speed can also be adjusted according to the same or different factors as those used for determining the frequency of variation. For example, the amplitude can be increased or decreased for a correspondingly wider or narrower weld joint 80, respectively. The amplitude is 5 equal to the difference in speed between the average speed  $S_{avg}$  and either the maximum or minimum speeds  $S_{max}$ ,  $S_{min}$ . That is, the amplitude is one half of the difference between the maximum speed  $S_{max}$  and the minimum speed  $S_{min}$ . According to one embodiment of the invention, the pin 24 rotates at a speed of between about 100 and 3000 RPM, and the amplitude is between about 1% and 200% 10 of the average rotational speed  $S_{avg}$  of the pin 24. Thus, the minimum rotational speed  $S_{min}$  can be less than 99% of the average rotational speed  $S_{avg}$ , and the maximum rotational speed  $S_{max}$  can be greater than 101% of the average rotational speed  $S_{avg}$  of the pin 24. For example, if the average rotational speed  $S_{avg}$  of the pin 15 24 is 100 RPM in the clockwise direction and the amplitude of the variation in rotational speed is 50% of the average rotational speed  $S_{avg}$ , the minimum speed  $S_{min}$  is about 50 RPM (clockwise) and the maximum speed  $S_{max}$  is about 150 RPM (clockwise).

Further, the amplitude of the variation in rotational speed can be greater than the average rotational speed  $S_{avg}$  of the pin 24 so that the rotational direction of the 20 pin 24 changes during operation. According to one embodiment of the invention, the average rotational speed  $S_{avg}$  is less than 100 RPM and has an amplitude of variation that is between about 100 and 1000 RPM. Thus, the pin 24 can cyclically reverse rotational direction to rotate alternately in the clockwise and counterclockwise directions, with an average speed that can be zero or greater than zero. For example, 25 if the average rotational speed  $S_{avg}$  of the pin 24 is about 100 RPM in a clockwise direction and the amplitude of the variation in rotational speed is about 150% of the average rotational speed  $S_{avg}$ , the minimum speed  $S_{min}$  is about 50 RPM in the counterclockwise direction, and the maximum speed  $S_{max}$  is about 250 RPM in the clockwise direction. Alternatively, as illustrated in Figure 3, the pin 24 can have no 30 average rotational speed  $S_{avg}$  (i.e.,  $S_{avg} = 0$  RPM) and an amplitude that is greater than zero. Thus, the pin 24 reverses direction at times  $T_1$ ,  $T_2$ ,  $T_3$ ,  $T_4$ ,  $T_5$  during the operation illustrated in Figure 3 to rotate successively in the clockwise and counterclockwise directions, attaining a maximum speed in each direction equal to the maximum and minimum speeds  $S_{max}$ ,  $S_{min}$ , respectively.

A reduction in the rotational speed of the pin **24** generally reduces the frictional heat generated between the pin **24** and the workpiece **60**. Thus, in those cases where the rotational speed of the pin **24** is less than about 100 RPM during at least some times of operation, e.g., where the rotational direction of the pin **24**

5 reverses cyclically, the shoulder **22** of the tool **20** can be structured to sufficiently frictionally engage the workpiece **60** to plasticize the workpiece **60** or nearly plasticize the workpiece **60** so that the pin **24** can be moved through the workpiece **60** even when the rotational speed of the pin **24** is reduced. For example, the diameter of the shoulder **22** can be five times the diameter of the pin **24** or greater so that the

10 shoulder **22** acts over a relatively large area proximate to the pin **24**.

The rotational speed of the pin **24** can be adjusted according to other patterns or models of variation besides the sinusoidal variation illustrated in Figures 2 and 3. For example, the variation can be characterized by a shape that is sawtoothed, ramped, rectangular or triangular stepped, and the like. In addition, the speed of the

15 pin **24** can be decreased and increased to different minimum and maximum speeds during successive variations. For example, the rotational speed can be decreased and increased to speeds that are predetermined or randomly selected. Further, the frequency of variation can also be constant or varied throughout a welding operation. For example, the rotational speed of the pin **24** can be constant during some periods

20 and varied during others.

The adjustment of the rotational speed of the pin **24** can be controlled by the controller **50**, e.g., according to a schedule or program stored in a memory of the controller **50**. In this regard, the controller **50** can communicate with a power source, such as the power supply **42**, that provides electrical power to the actuator **30**.

25 Further, the controller **50** can function as a current or voltage regulation device for varying the electric current that is provided to the actuator **30**, thereby adjusting the speed of the actuator **30** and the rotational speed of the pin **24**. Alternatively, the controller **50** can digitally control the actuator **30**, e.g., by transmitting a digital electronic signal to the actuator **30** for controlling the rotational actuation of the pin

30 **24**.

Further, as shown in Figure 1, the apparatus **10** can include a heater such as an induction heater **40** for heating the material of the workpiece **60** during the welding operation. The induction heater **40** is electrically connected to a power supply **42** and configured to induce an electric current in the workpiece **60**, such that the workpiece

60 is resistively heated to a desired temperature. Alternatively, other types of heaters can be used such as lasers, electric resistive heaters, gas or other flame heaters, and the like. In some cases, inductance heating can be used to heat thick workpieces uniformly throughout the thickness of the workpiece, and other surface heaters, such 5 as lasers, can be used to heat thin workpieces. Regardless of the type of heater 40 used in the apparatus 10, the workpiece 60 can be heated to a desired temperature before, during, and/or after being friction stir welded by the tool 20.

According to one embodiment of the present invention, the induction heater 40 is used to preheat the workpiece 60 to a desired temperature before friction stir 10 welding. The preheating of the workpiece 60 can reduce the friction that is required between the pin 24 and the workpiece 60 for plasticizing the material of the workpiece 60 and friction stir welding the workpiece 60. Thus, in some embodiments, preheating can increase the speed at which the pin 24 can be moved through the workpiece 60 and/or reduce the forces that must be applied through the 15 pin 24 to weld the workpiece 60. The desired amount of preheating can vary according to the thickness, material, or other mechanical properties of the workpiece 60, the rotational speed of the pin 24, the speed at which the pin 24 is moved through the interface 70 to form the weld joint 80, the size of the pin 24, the initial temperature of the workpiece 60, the type of weld joint 80 being formed, the desired 20 mechanical properties of the weld joint 80, and the like. The induction heater 40 can be used to heat the workpiece 60 to a “preheat temperature” that is less than the plasticizing temperature of the workpiece 60. For example, the induction heater 40 can heat the workpiece 60 by at least 50° F to a temperature that is less than the plasticizing temperature of the workpiece 60.

25       The induction heater 40 can be configured proximate to the friction stir welding tool 20 and configured to heat only a portion of the workpiece 60 at a time. Further, the induction heater 40 can be configured to move along the workpiece 60 in a path preceding the motion of the friction stir welding tool 20. Thus, the induction heater 40 can be configured to heat a portion of the workpiece 60 that is proximate to 30 the pin 24 such that portions of the workpiece 60 away from the region of the friction stir weld joint 80 are heated only minimally or not at all. In some embodiments, the induction heater 40 can be connected to the friction stir welding tool 20 or actuator 30 or otherwise maintained at a uniform distance from the friction stir welding tool 20. Thus, the induction heater 40 can be moved simultaneously, and at a similar speed,

with the friction stir welding tool 20. Alternatively, the induction heater 40 can be controlled separately from the friction stir welding tool 20, e.g., by the controller 50, such that the heater 40 moves independently from the welding tool 20. Thus, the heater 40 can be moved at a different speed than the tool 20 and adjusted to be closer 5 or farther from the tool 20 according to the desired heating. Further, the amount of heating of the workpiece 60 achieved by the induction heater 40 can be adjusted during a welding operation, e.g., according to different physical properties of the workpiece 60 at different locations, adjustments in the rotational speed of the pin 24, the speed of the pin 24 through the workpiece 60, and the like.

10        Although the invention is not limited to any particular theory of operation, it is believed that the changes in rotational speed of the pin 24 affect the movement of the plasticized material of the workpiece 60 during welding. In particular, it is believed that increases and decreases in the rotational speed of the pin 24 generally result in an increase in the mixing of the plasticized material of the workpiece 60. In addition, it  
15      is believed that the heating of the workpiece 60 by the heater 40 can reduce the friction between the pin 24 and the workpiece 60 while still allowing the workpiece 60 to be plasticized. Thus, the variation in the rotational speed of the pin 24 can increase the mixing of the plasticized material even if the frictional forces between the pin 24 and the plasticized material are reduced, e.g., due to the heating of the  
20      workpiece 60 by the heater 40. In other embodiments of the invention, the rotational speed of the pin 24 can be varied without the use of the heater 40.

According to one embodiment of the present invention, the friction stir weld joint 80 is formed by moving the rotating friction stir welding tool 20 into contact with the workpiece 60 so that the stirring portion of the pin 24 and the shoulder 22  
25      frictionally engage the workpiece 60. The rotating friction stir welding tool 20 can be moved through the workpiece 60 along a predetermined path to thereby form the elongate weld joint 80. Thus, the material of the workpiece 60 can be mixed by the pin 24, and the grain size of the material can be refined, thereby improving the material properties of the material at the joint 80.

30        For example, the weld tool 20 can be configured at an edge of workpiece 60, rotated in a direction 12, and urged in a direction 14 through the workpiece 60 such that the shoulder 22 contacts the surface of the workpiece 60, thereby constraining the axial movement of the plasticized material of the workpiece 60. Alternatively, if the weld joint 80 is to begin or end at a point inward from the edge of the workpiece 60,

the tool **20** can be urged, or “plunged,” into the workpiece **60** at the start of the weld joint **80** and/or subsequently retracted from the workpiece **60** after welding the workpiece **60**. In either case, the urging force of the shoulder **22** against the workpiece **60** can be opposed by an anvil or other support device (not shown)

5        positioned opposite the shoulder **22** or by a second shoulder connected to the pin **24** and positioned opposite the workpiece **60** from the shoulder **22**. Thus, the workpiece **60** can be “sandwiched” between the shoulder **22** and another shoulder or support device proximate to the pin **24** during friction stir welding. Advantageously, the shoulder **22** and the second shoulder or other support device can create a seal that

10      prevents the plasticized material from being extruded therefrom. Thus, planar or otherwise desired contours can be formed on the opposing sides of the workpiece **60** at the weld joint **80**. If two shoulders are attached to the pin **24**, the two shoulders can restrain the tool **20** axially against the workpiece **60** so that little or no axial force needs to be applied to the tool **20** during welding. As the tool **20** is urged in direction

15      **14**, the induction heater **40** heats the workpiece **60** and is moved in direction **16** in a path to precede the tool **20** so that the workpiece **60** is preheated by the heater **40** and subsequently plasticized by the tool **20**. Further, the rotational speed of the tool **20** in direction **12** is cyclically adjusted, as described above, thereby mixing the plasticized material of the workpiece **60**.

20        According to another embodiment of the present invention, the pin **24** can include more than one portion, each portion being independently rotatable. For example, the pin **24** of the tool illustrated in Figure 4 includes first and second portions **25a**, **25b**. The second portion **25b** is connected to a shaft **28** that extends through an aperture **26** defined by the first portion **25a** such that the first portion **25a** can be engaged to the shoulder **22** and a first actuator **30a**, while the second portion **25b** is engaged by a second actuator **30b**. The actuators **30a**, **30b** can rotate the two portions **25a**, **25b** with different cyclic variations or according to different predetermined schedules. For example, the actuators **30a**, **30b** can rotate the two portions **25a**, **25a** with the same or different average speeds, minimum and maximum speeds, directions of rotation, frequencies of variation, magnitudes of variation, variation profiles or characteristics, timing of variation, and/or other aspects of rotation. Further, the first portion **25a** can be configured to extend substantially through the first structural member **62**, and the second portion **25b** can be configured to extend substantially through the second structural member **64**. Thus, the first and

second portions **25a**, **25b** can be rotated according to the material properties of the first and second structural members **62**, **64**, respectively, so that each portion **25a**, **25b** effectively plasticizes and mixes the material of the respective member **62**, **64**.

Alternatively, the two portions **25a**, **25b** can be integral members or otherwise connected so that the portions **25a**, **25b** rotate together at the same rotational rate and with the same variation. For example, as shown in Figure 5, the two portions **25a**, **25b** can be a unitary member that extends from the shoulder **22**. Further, the first and second portions **25a**, **25b** can be selected or formed according to the material properties of the structural members **62**, **64**, the type of weld joint **80** being formed, and the like. For example, the diameter of the first structural portion **25a** can be greater than the diameter of the second portion **25b** so that the pin **24** frictionally engages more of the material in the first structural member **62** than in the second structural member **64**. As a result of the dissimilar diameters of the two portions **25a**, **25b**, rotating the first and second portions **25a**, **25b** at a equal rotational rate results in different speeds of the outer surfaces of the portions **25a**, **25b**. In particular, the outer surface of the first portion **25a** moves faster relative to the workpiece **60** than the outer surface of the second portion **25b**. In addition, the two portions **25a**, **25b** with dissimilar diameters can be structured to be rotated at different rotational rates, e.g., as described in connection with Figure 4.

In other embodiments of the present invention, the pin **24** can define three or more portions, each of which can define a different diameter and/or be structured for independent rotation. For example, Figure 6 illustrates a tool **20** having a pin **24** that includes first, second, and third portions **25a**, **25b**, **25c**. As shown, the first and third portions **25a**, **25c** are larger in diameter than the second portion **25b**. Thus, the first and third portions **25a**, **25c** can be used to frictionally engage a wider region of material in the workpiece **60** and/or to define channels on the opposite surfaces of the workpiece **60**. Each of the portions **25a**, **25b**, **25c** can be independently rotatable, or connected to one or more of the other portions **25a**, **25b**, **25c** and rotated therewith.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are

employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.